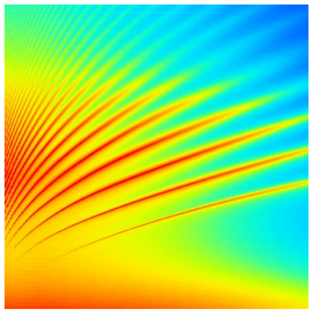
The role of the near-surface flows.

Cameron & Schüssler



Convection theory predicts a high diffusivity – dynamo models require a low diffusivity.

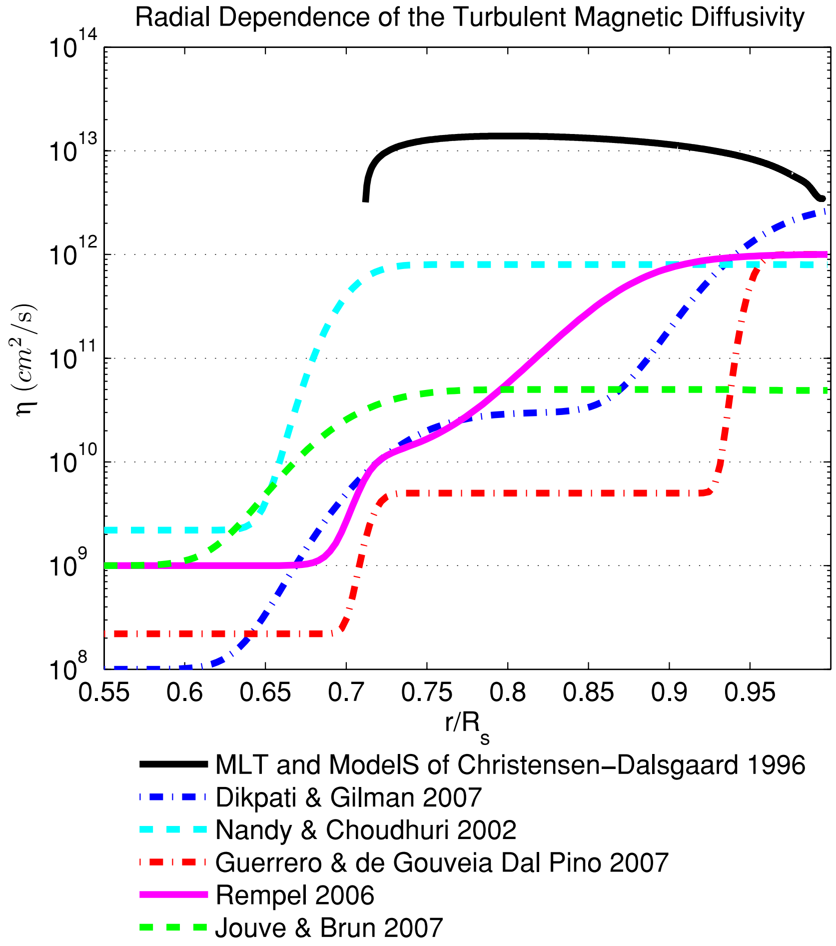
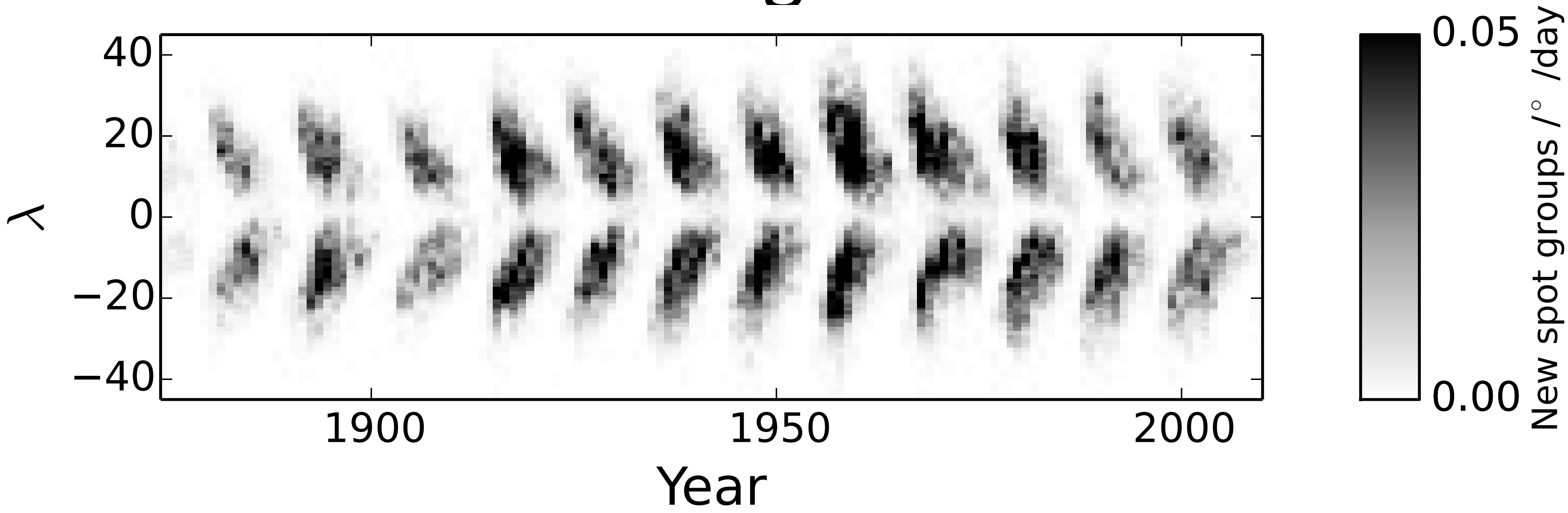


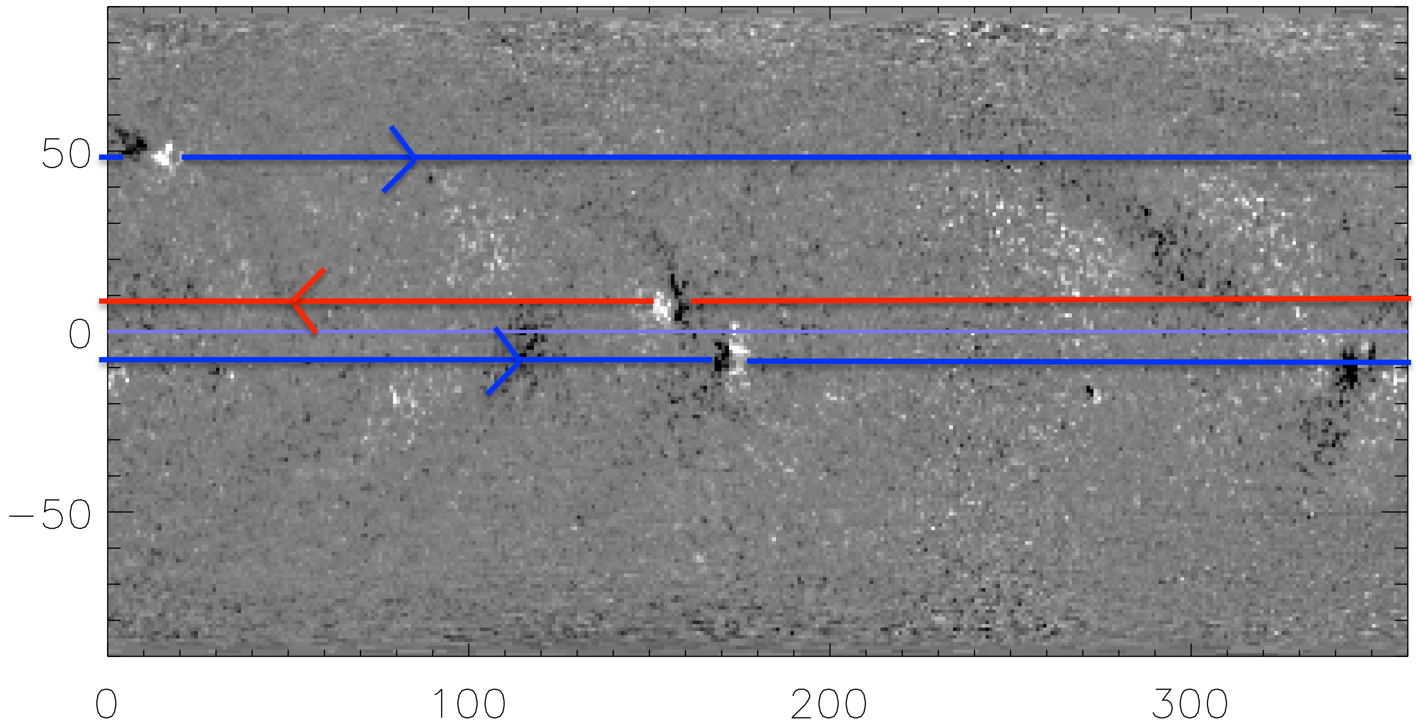
Figure 1. Different diffusivity profiles used in kinematic dynamo simulations. The solid black line corresponds to an estimate of turbulent diffusivity obtained by combining mixing-length theory (MLT) and the Solar Model S. The fact that viable solutions can be obtained with such a varied array of profiles has led to debates regarding which profile is more appropriate. Nevertheless, it is well known that kinematic dynamo simulations cannot yield viable solutions using the MLT estimate.

Munoz-Jaramillo, Nandy & Martens (2011 ApJ 727 L23)

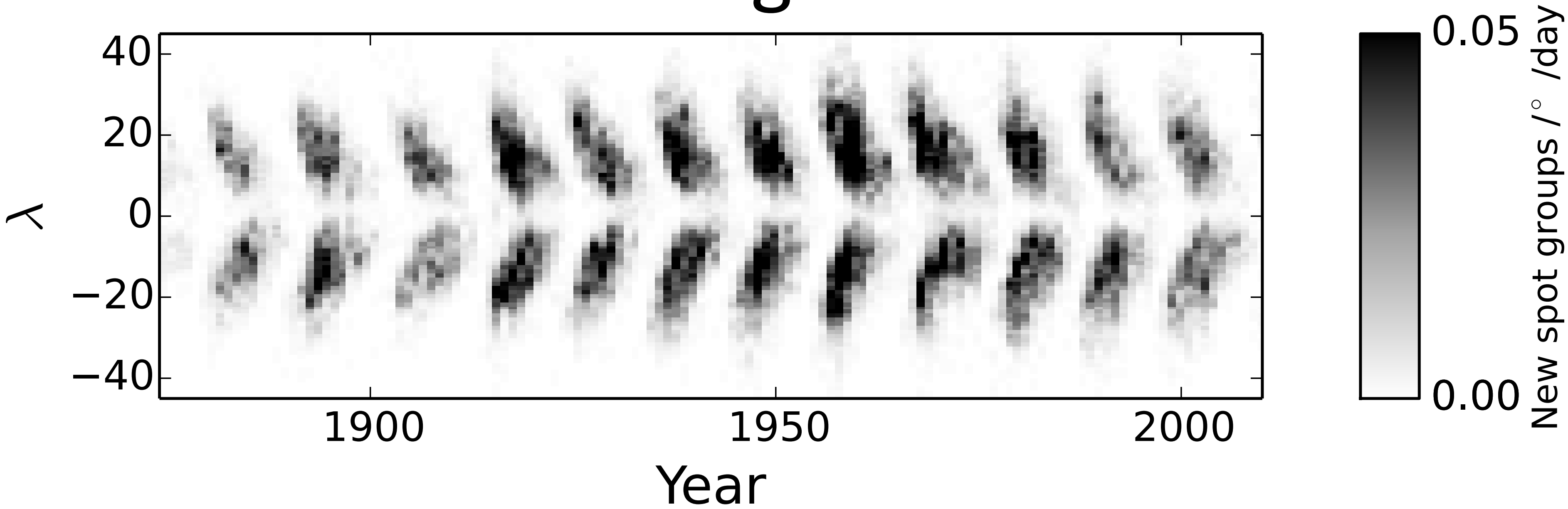
What we can observe is the butterfly diagram.



Sunspots are a measure of toroidal flux



What we can observe is the butterfly diagram.



What we measure:

Sunspot Number (t)

Mean $|\lambda|$(t)

HWHM(t)

(t based on years)

Waldmeier effect

-- Sunspot Number (t)

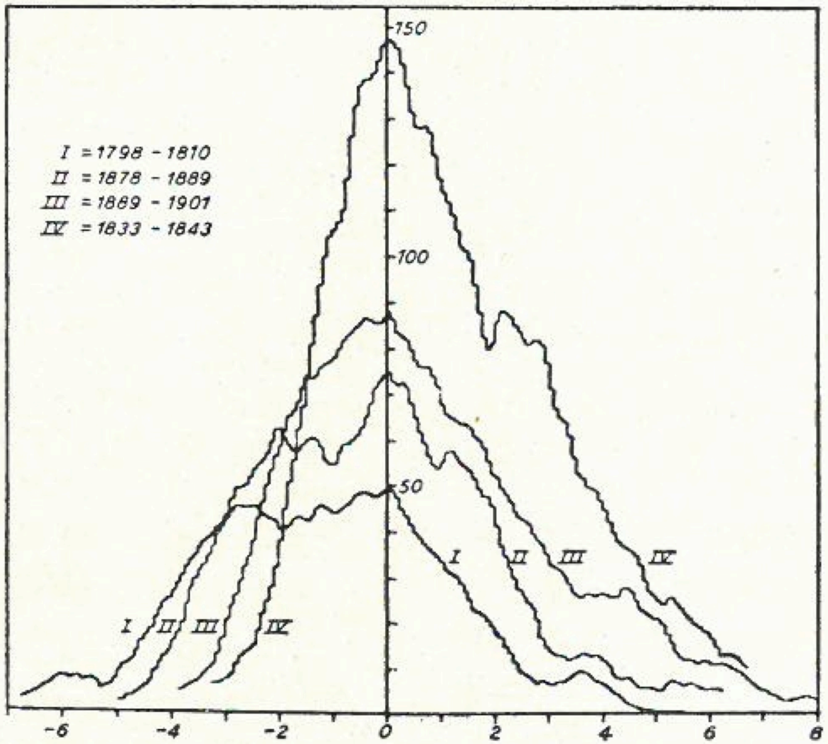


Abb. 39. Charakteristische Fleckenkurven nach M. Waldmeier. Ordinaten: ausgeglichene monatliche Relativzahlen. Abszissen: Abstände vom Maximum in Jahren.

From Waldmeier 1941

Waldmeier effect

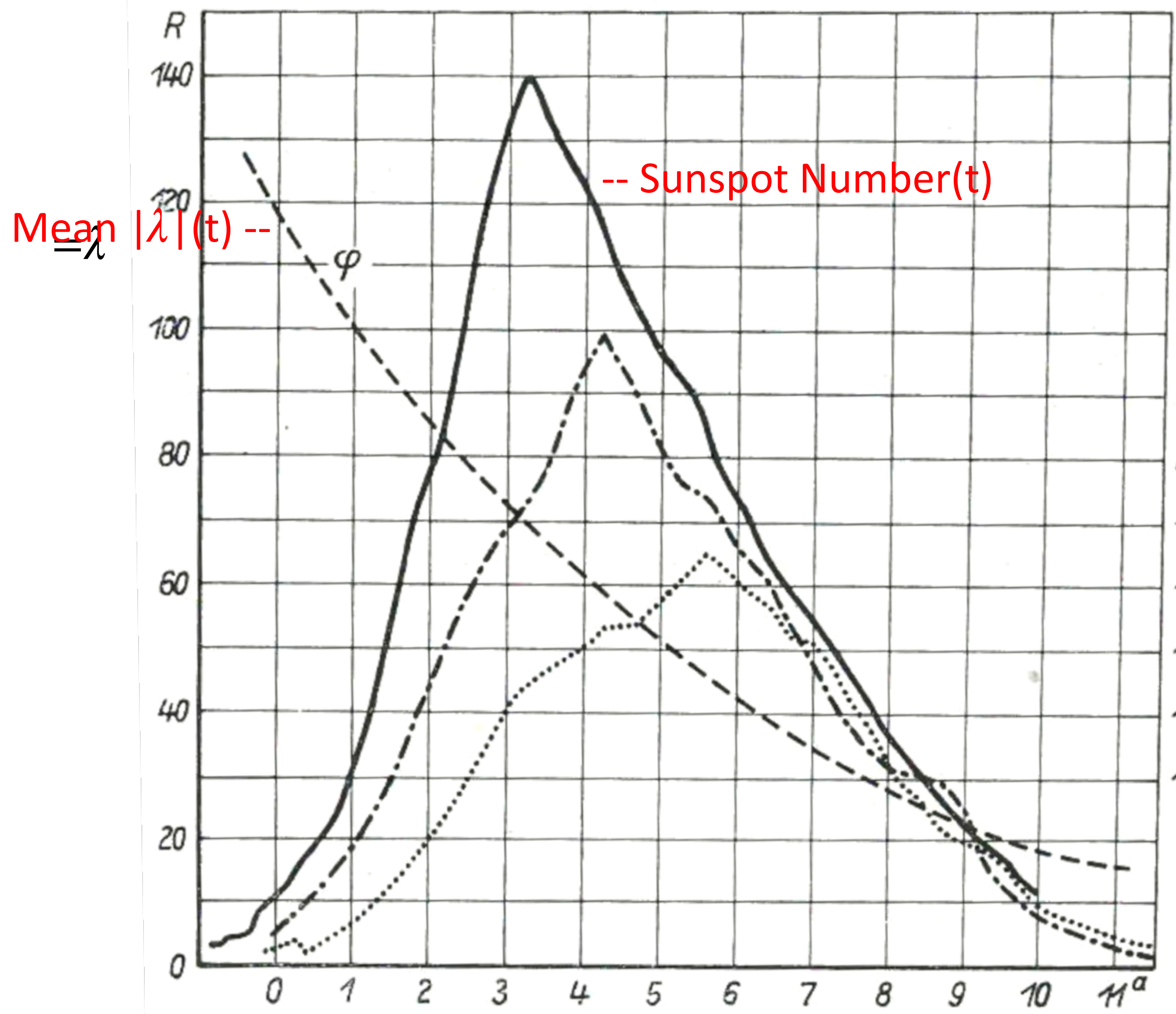
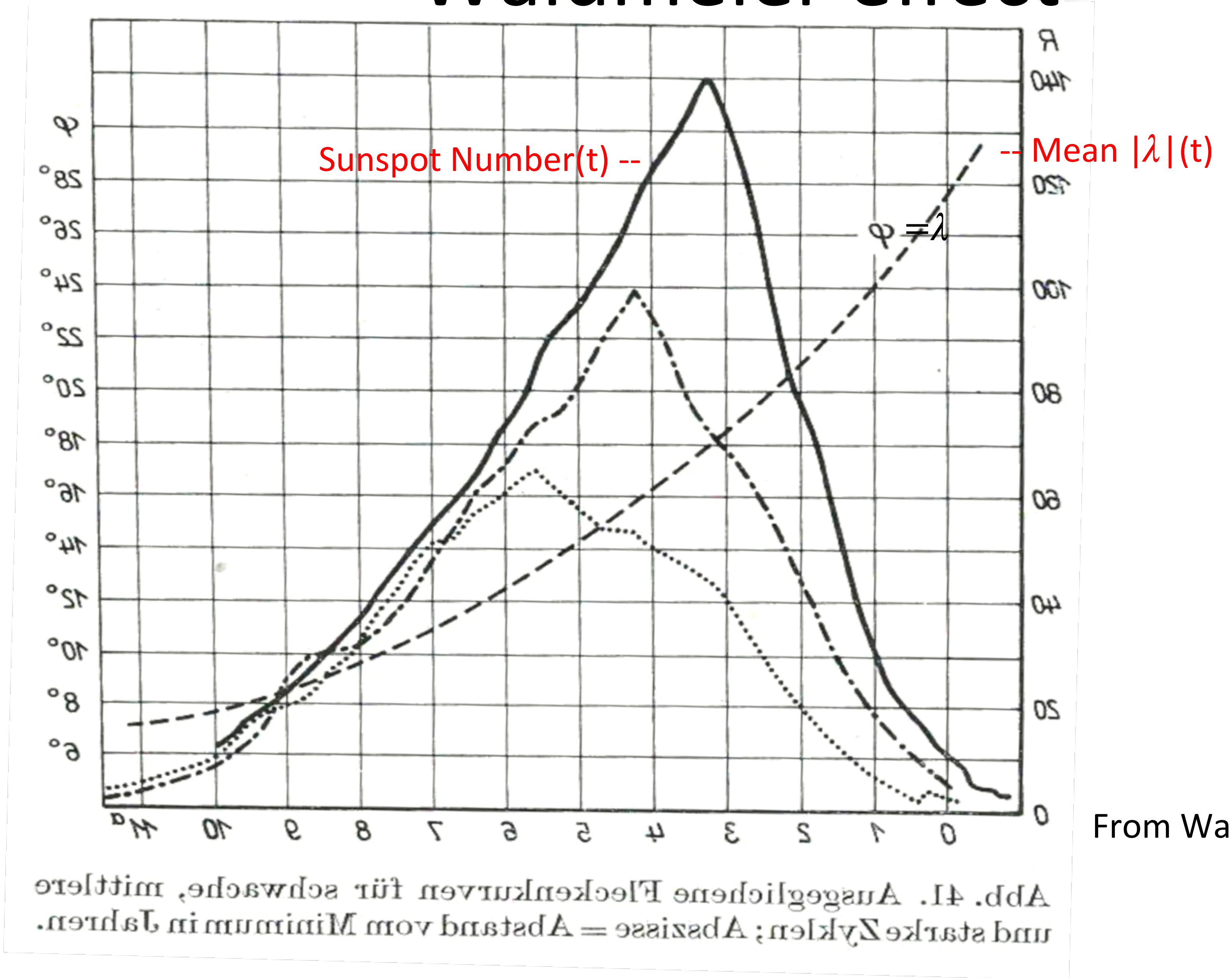


Abb. 41. Ausgeglichene Fleckenkurven für schwache, mittlere und starke Zyklen; Abszisse = Abstand vom Minimum in Jahren.

From Waldmeier 1955

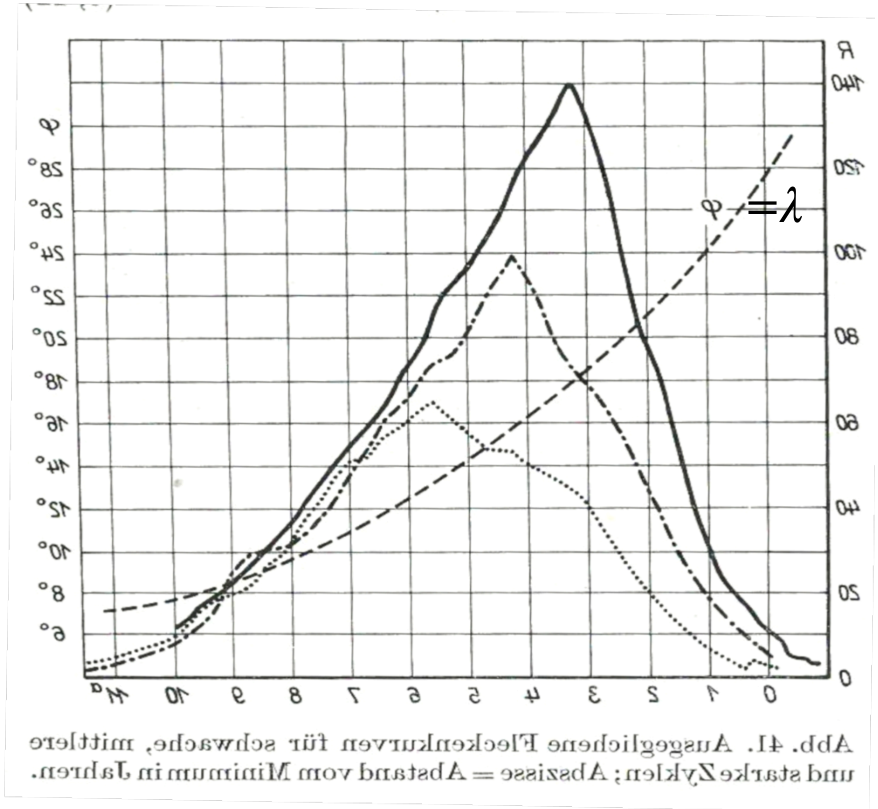
Waldmeier effect



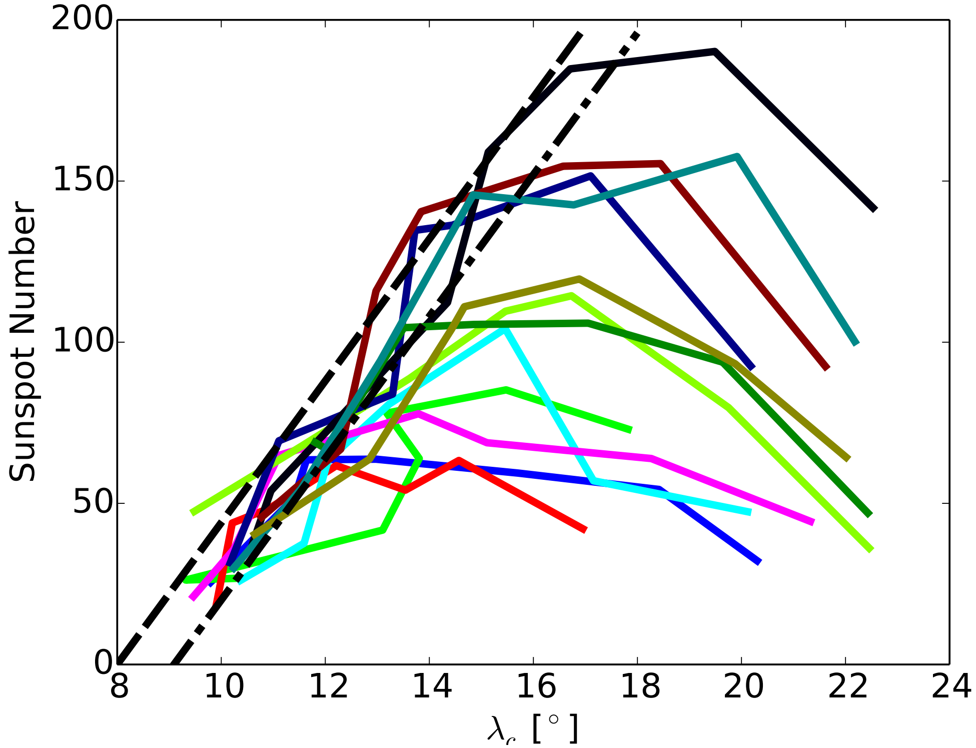
From Waldmeier 1955

Waldmeier effect

Sunspot Nzmber(t)
vs
Mean $|\lambda|$(t)



From Waldmeier 1955

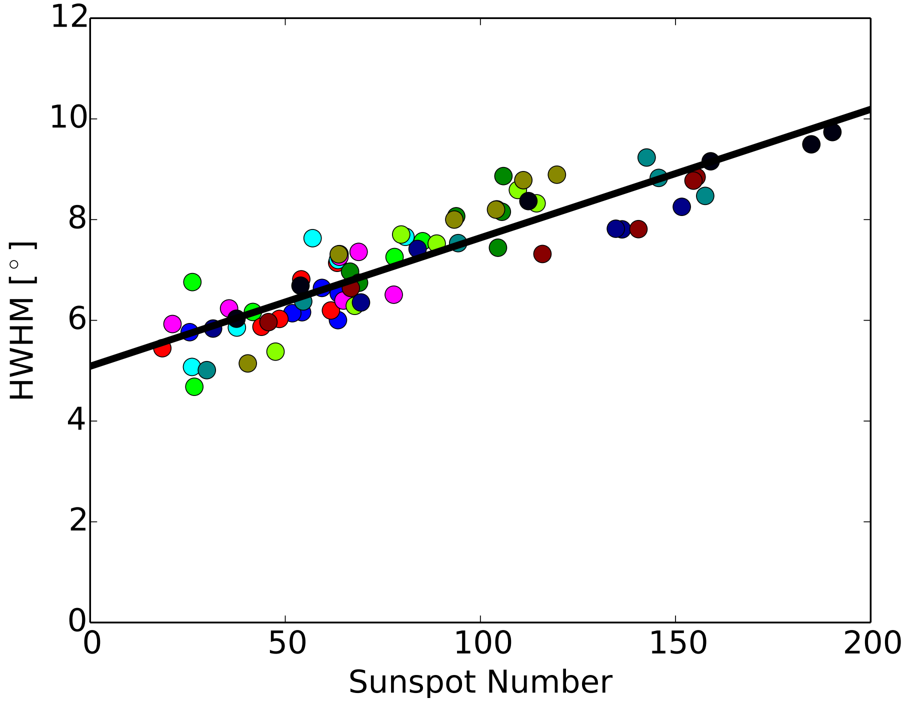


We can plot measured quantities against one another.

Sunspot Number (t)
Mean $|\lambda|$(t)
HWHM(t)

(t based on years)

HWHM(t)
vs
Sunspot Number (t)



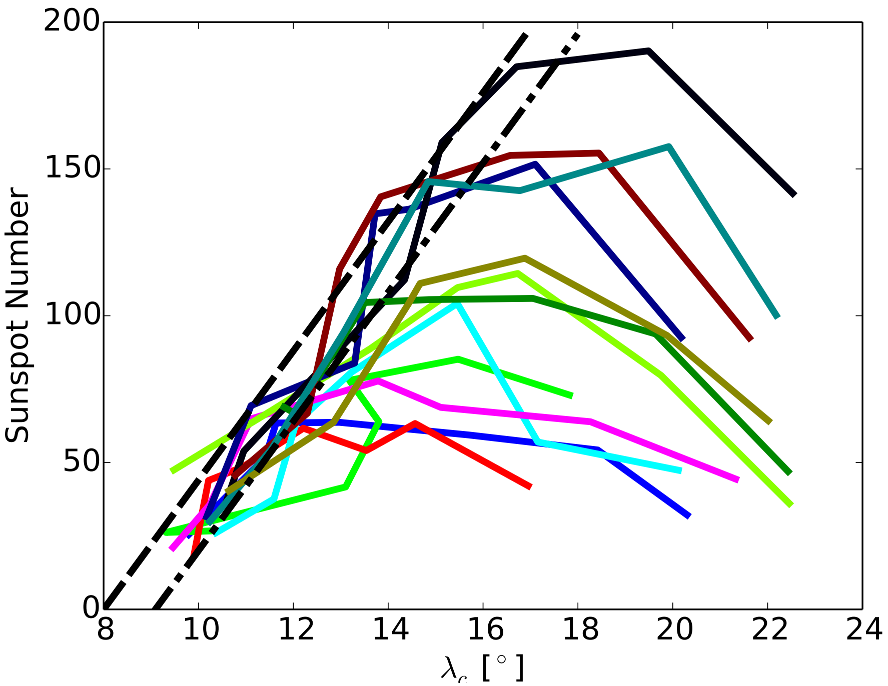
Different colors represent different cycles

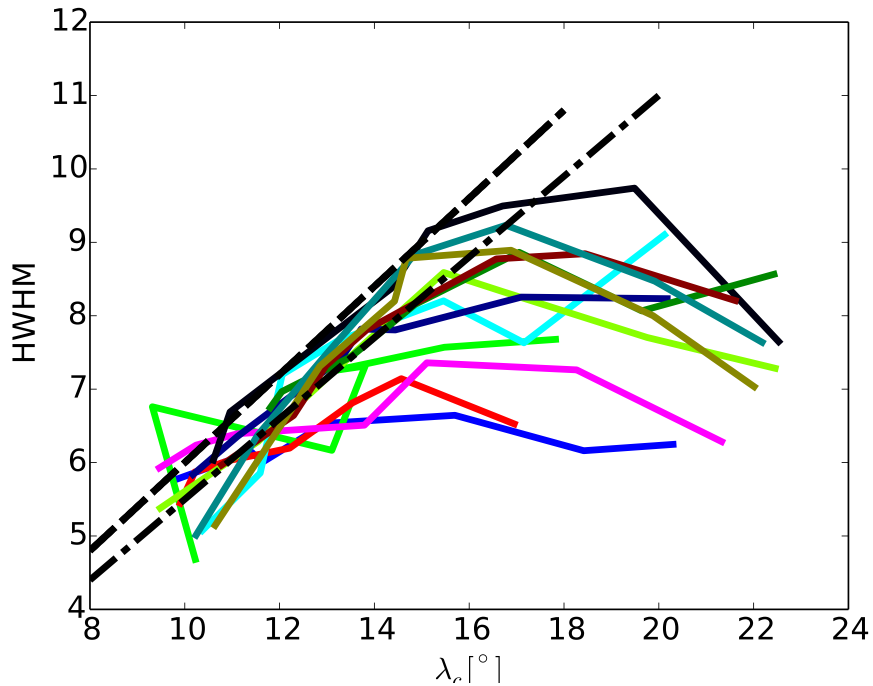
See also cycle-average studies:
Hathawy 2015
Solanki, Wenzler & Schmitt, 2008
Jiang, Cameron, Schmitt & Schüssler (2011)

Waldmeier effect

Sunspot Nzmber(t)
vs
Mean $|\lambda|$(t)

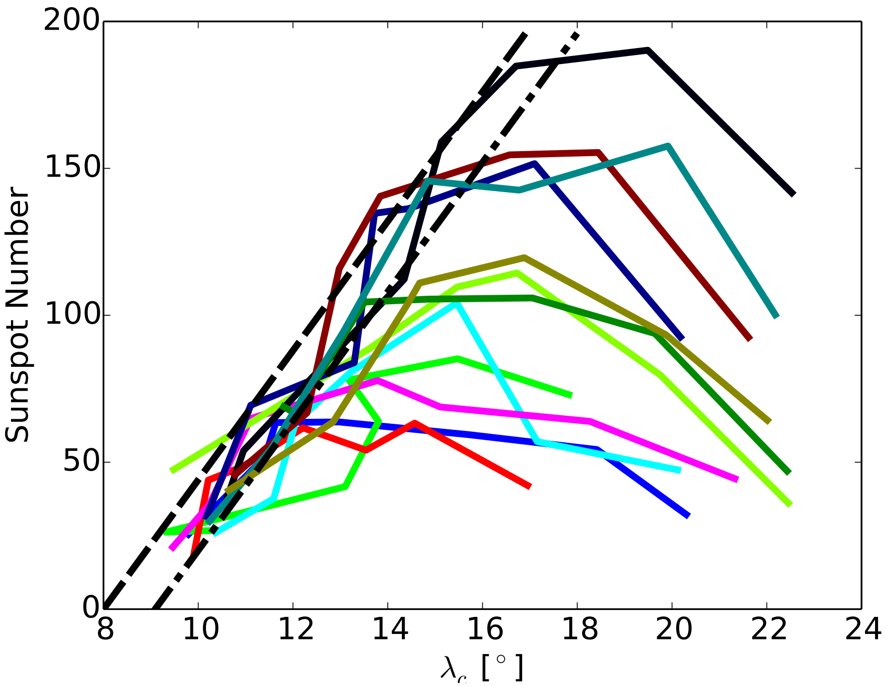
HWHM(t) vs Mean $|\lambda|$(t)



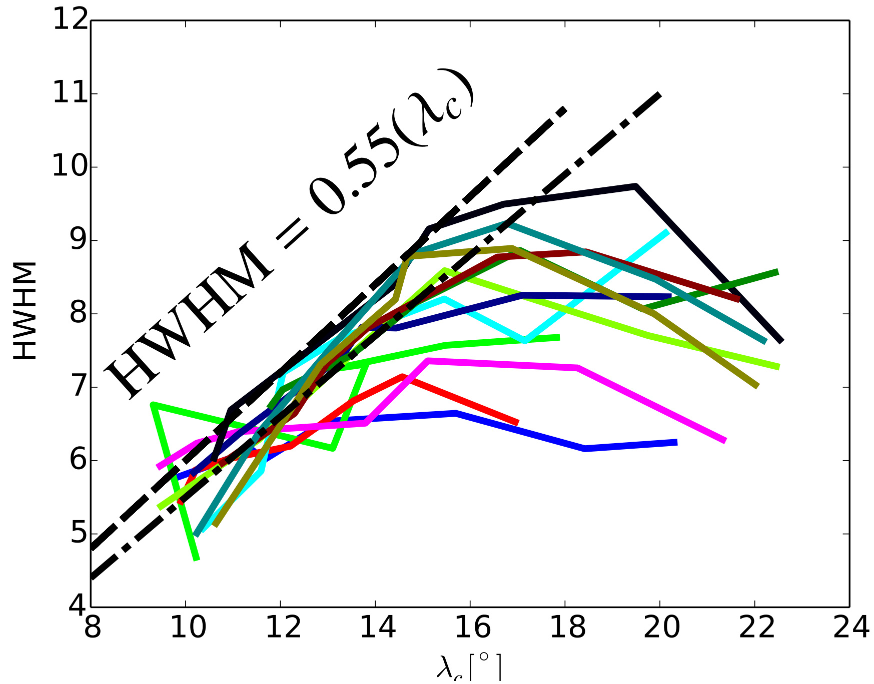


Waldmeier effect

Sunspot Nzmber(t)
vs
Mean |λ|(t)

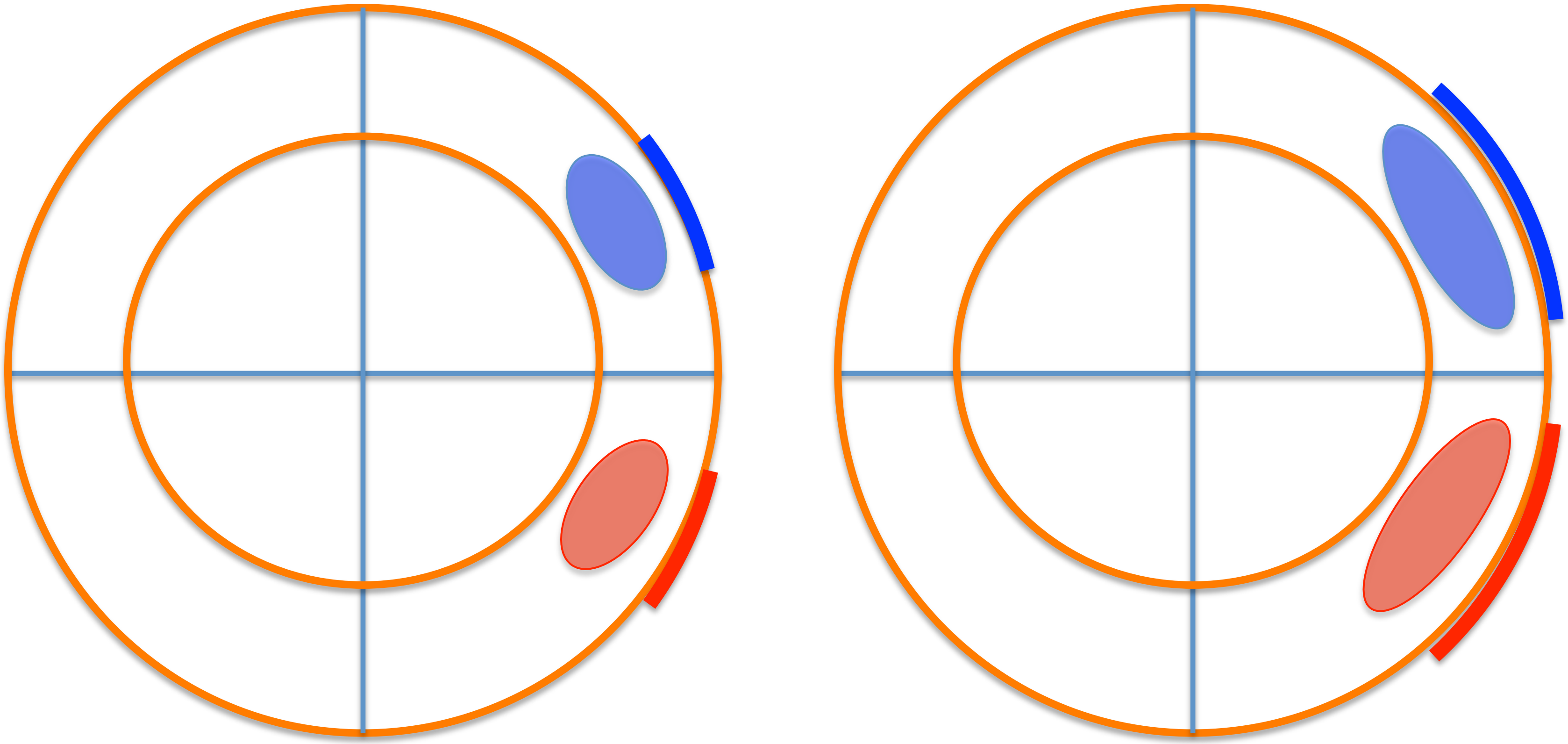


HWHM(t) vs Mean |λ|(t)



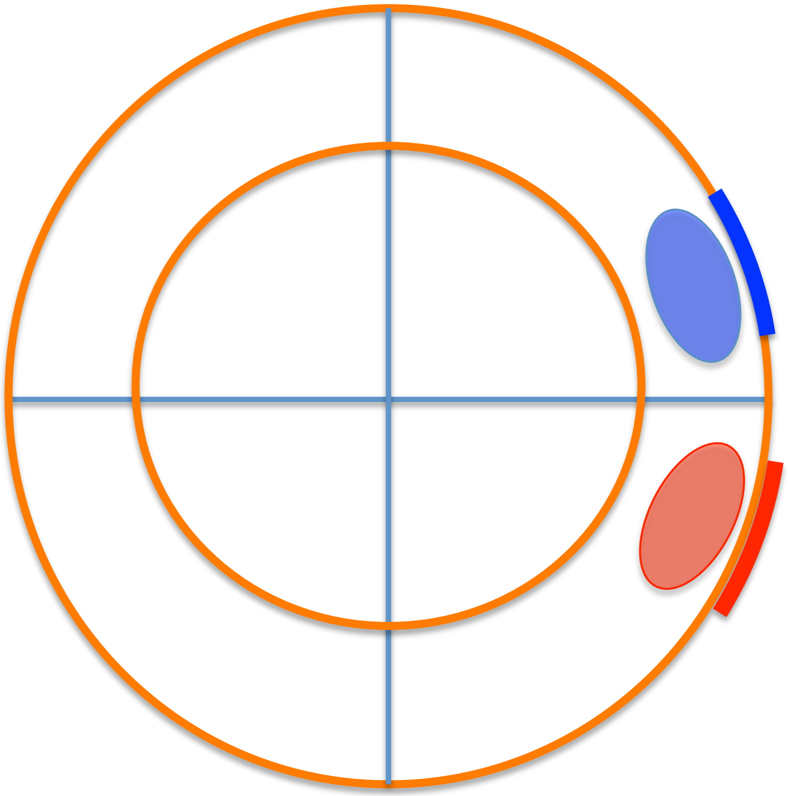
Sunspot number decreases when centre of active region belt moves
to within 1.8 HWHM of the equator!

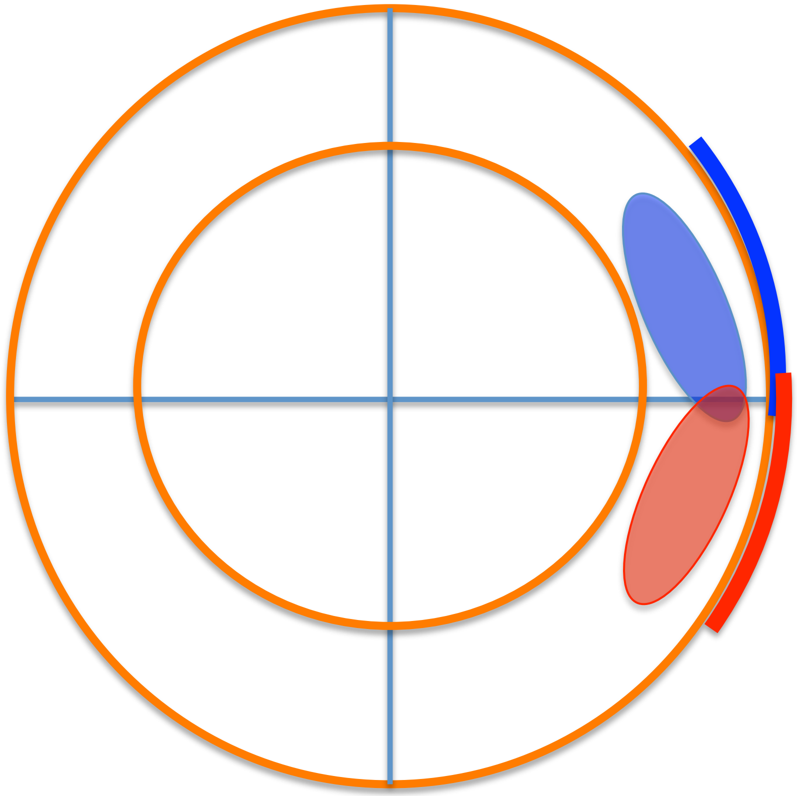
Interprettation



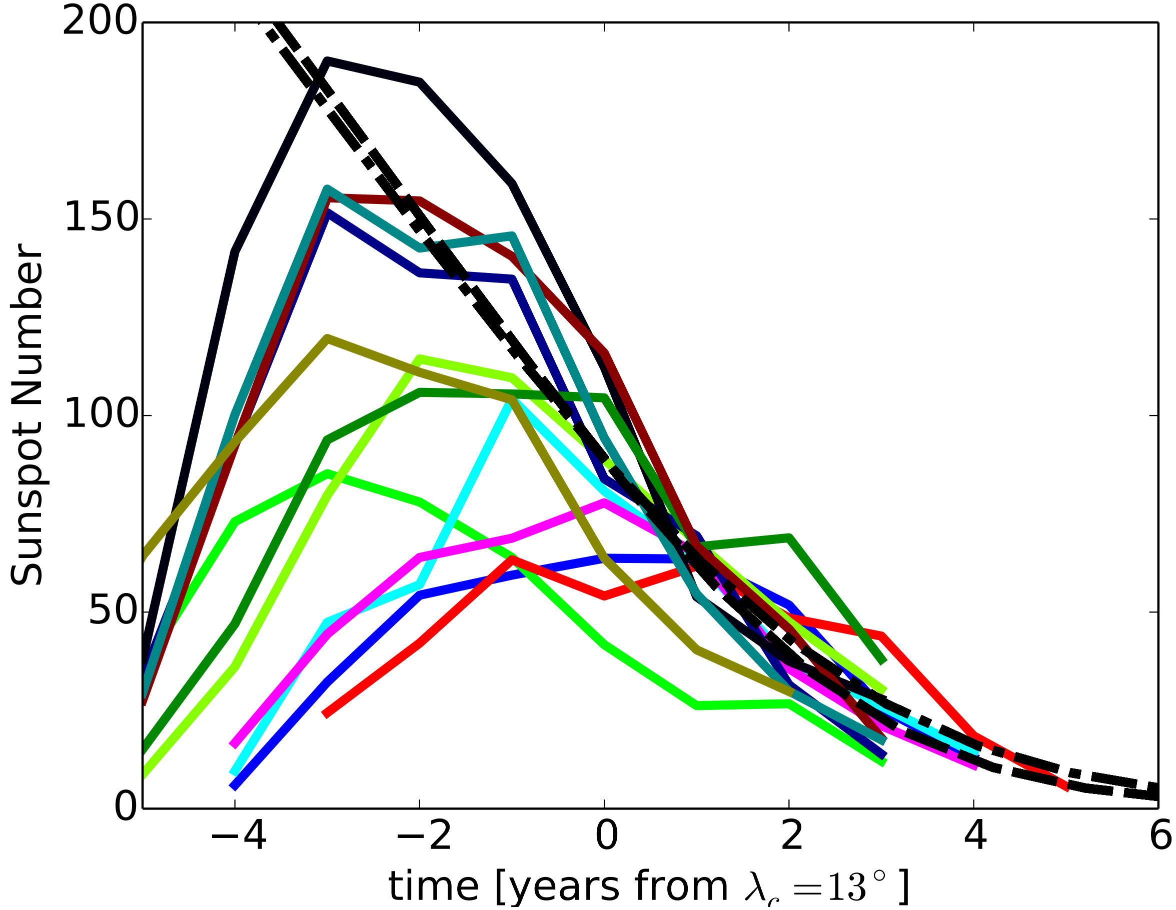
Weak cycle   Strong cycle

Interprettation


Weak cycle


Strong cycle

Determining the turbulent diffusivity



Model with

$$\frac{R_\odot^2}{R_c^2}\eta_{\rm turb} \;=\; 600\ {\rm km^2 s^{-1}}.$$

=> $$250\ {\rm km^2 s^{-1}} \le \eta_{\rm turb} \le 600\ {\rm km^2 s^{-1}}$$

Munoz-Jaramillo, Nandy & Martens (2011 ApJ 727 L23)

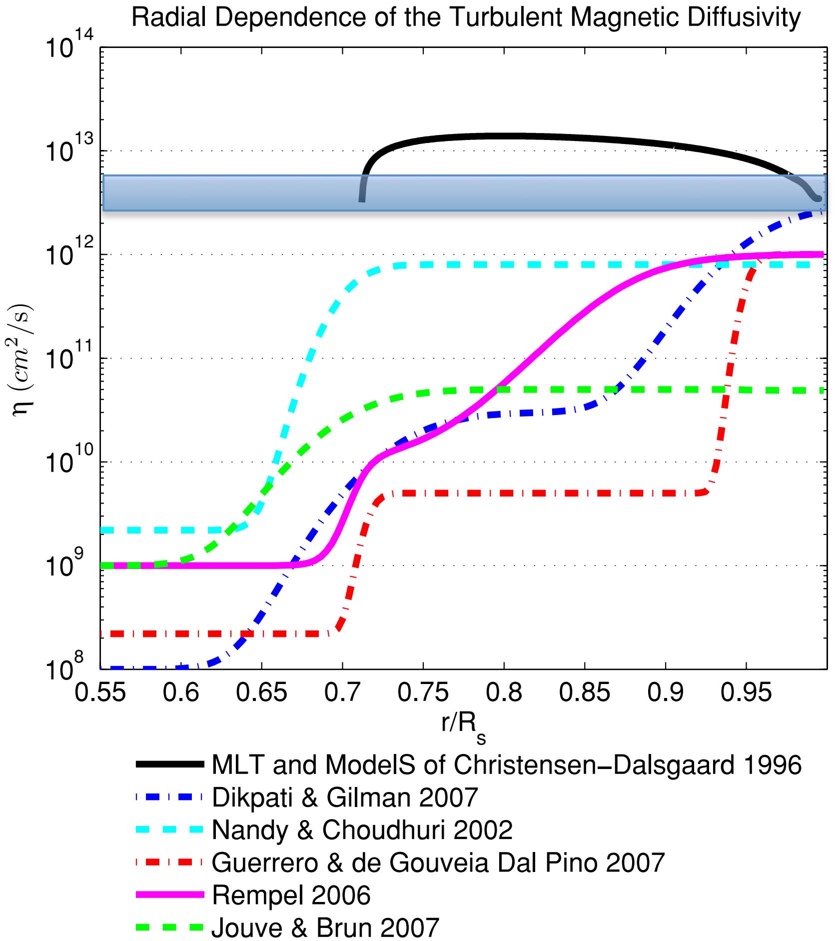


Figure 1. Different diffusivity profiles used in kinematic dynamo simulations. The solid black line corresponds to an estimate of turbulent diffusivity obtained by combining mixing-length theory (MLT) and the Solar Model S. The fact that viable solutions can be obtained with such a varied array of profiles has led to debates regarding which profile is more appropriate. Nevertheless, it is well known that kinematic dynamo simulations cannot yield viable solutions using the MLT estimate.

Conclusions: II

Turbulent diffusivity is 250—600 km^2/s where the toroidal flux is located

Evolution of the Sun‘s toroidal flux II

Munoz-Jaramillo, Nandy & Martens (2011 ApJ 727 L23)

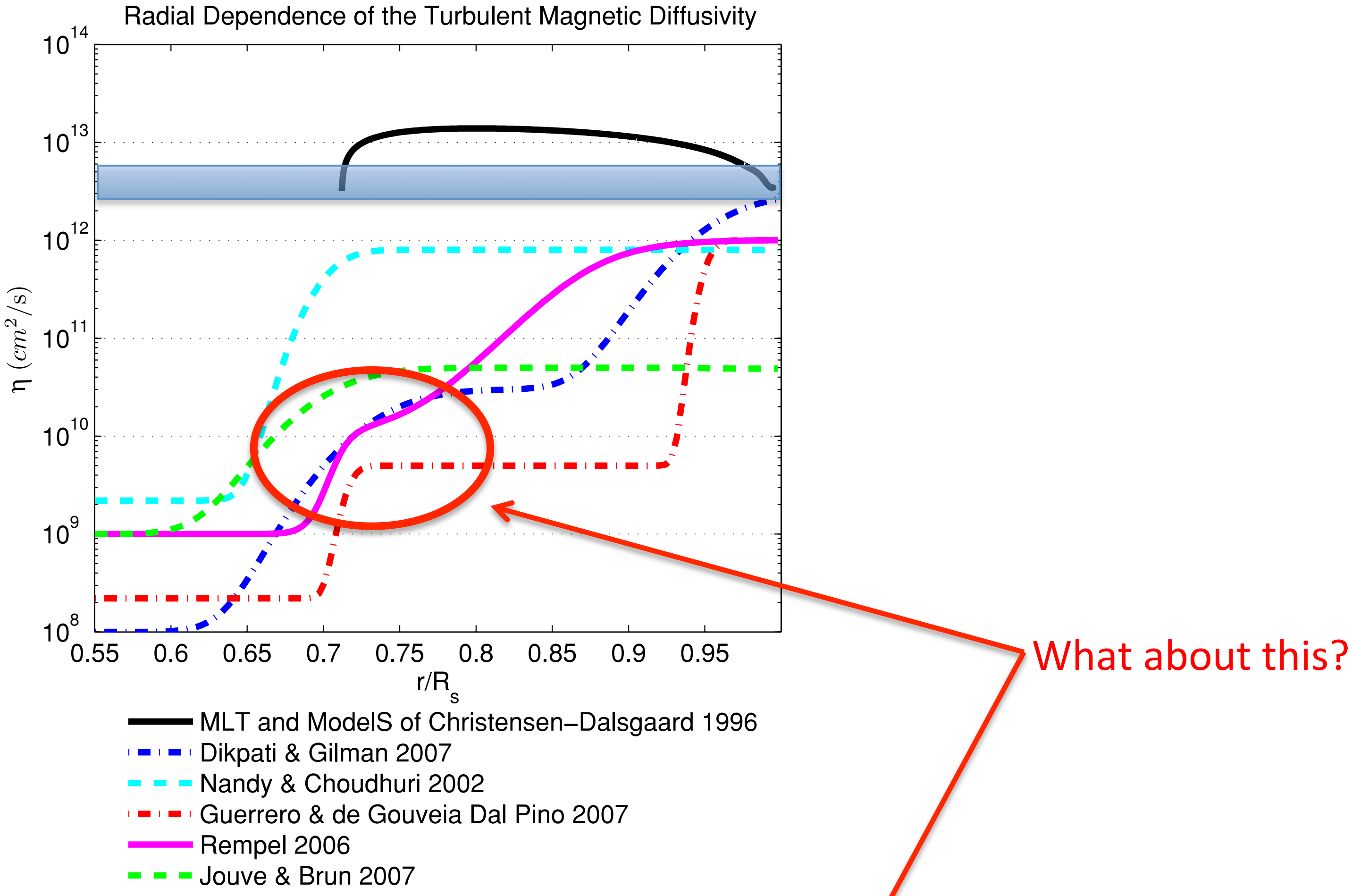


Figure 1. Different diffusivity profiles used in kinematic dynamo simulations. The solid black line corresponds to an estimate of turbulent diffusivity obtained by combining mixing-length theory (MLT) and the Solar Model S. The fact that viable solutions can be obtained with such a varied array of profiles has led to debates regarding which profile is more appropriate. Nevertheless, it is well known that kinematic dynamo simulations cannot yield viable solutions using the MLT estimate.

The butterfly wings maintain a HWHM of 6 degrees for many years (weak cycles) or the HWHM decreases (strong cycles).

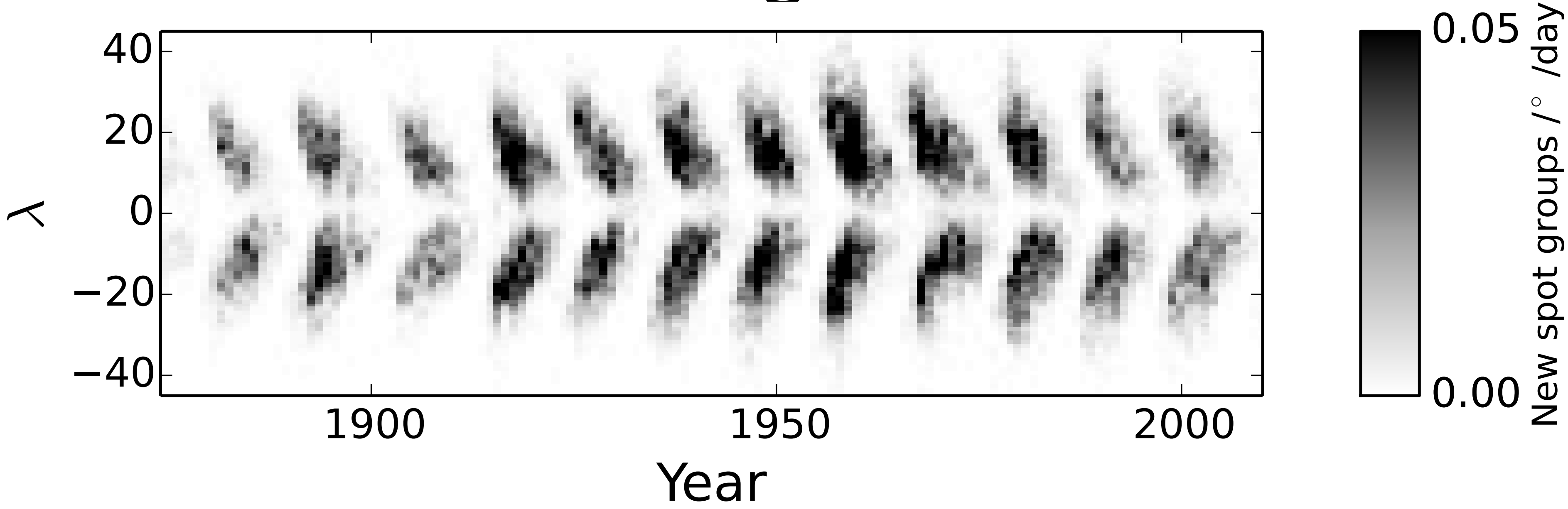
Why don‘t the butterfly wings diffuse outwards?

η_{turb}=250 km^2/s =53 $(°)^2$/year

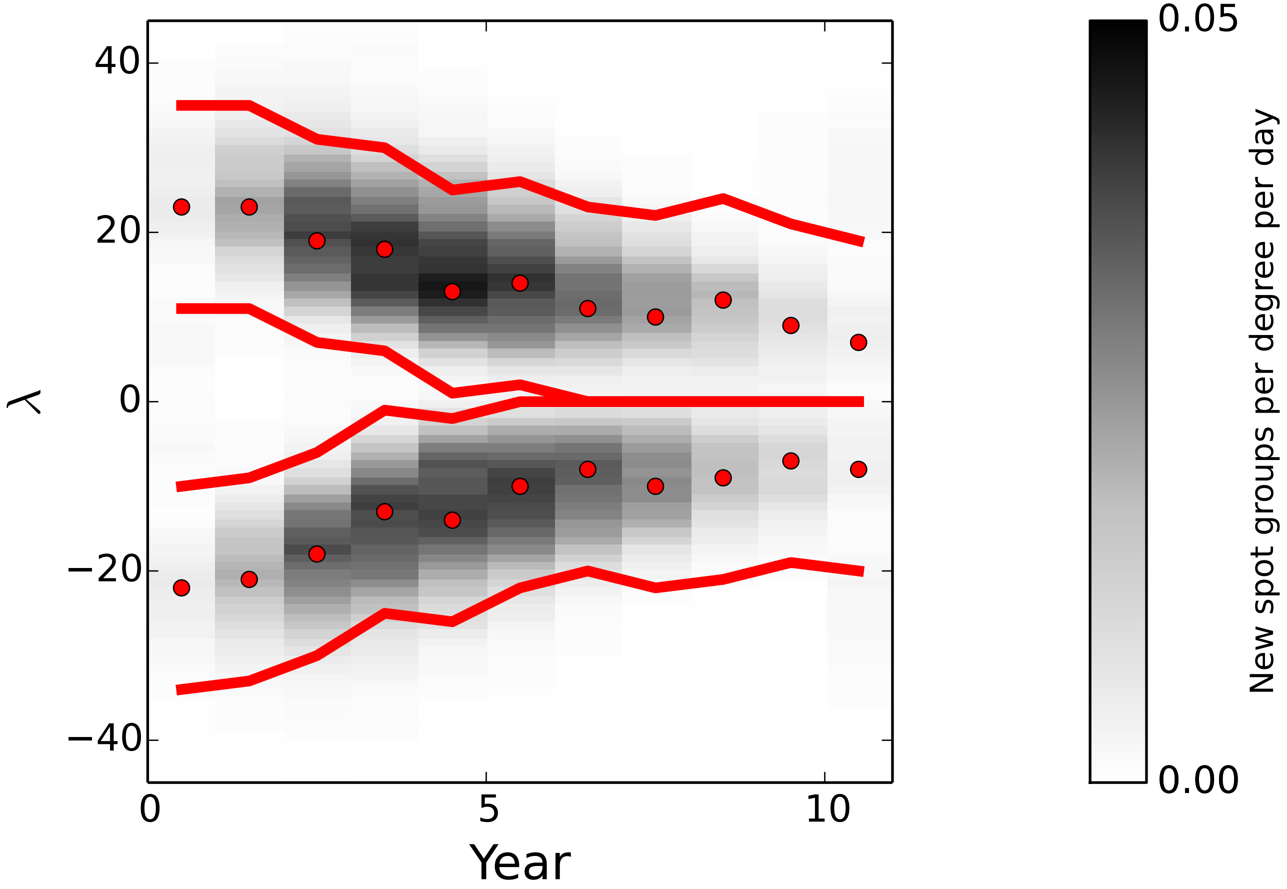
$\approx 7^2$ $(°)^2$/year

Suggests $\eta_{\mathrm{turb}} \ll$ 250 km^2/s ??

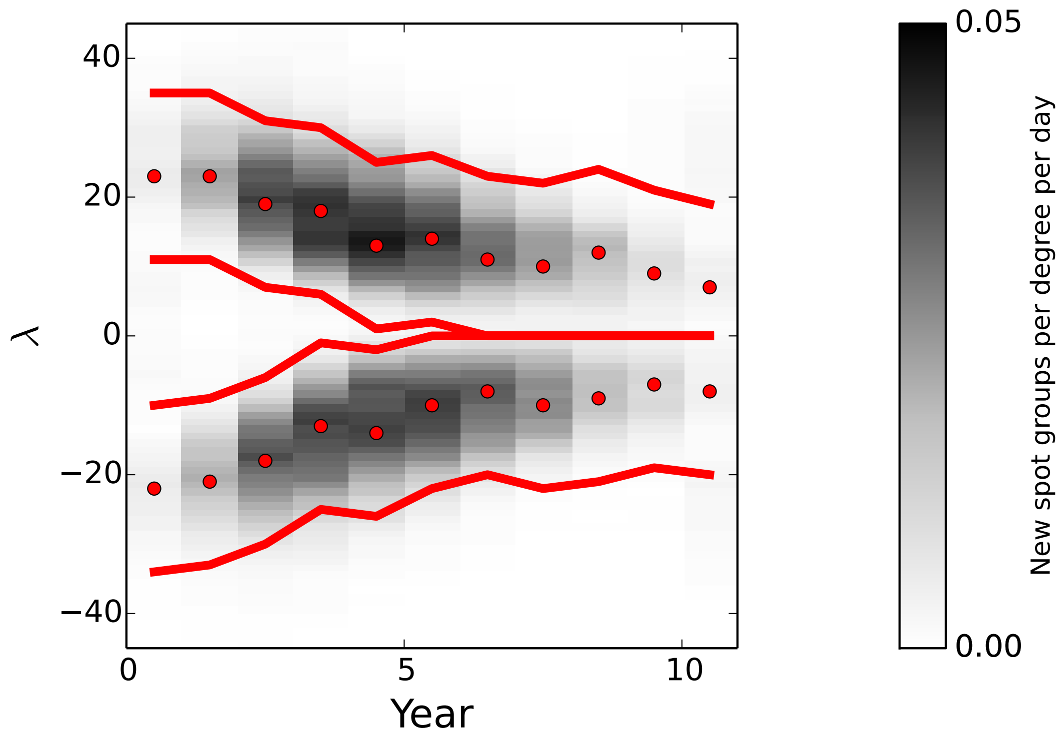
What we can observe is the butterfly diagram.



The average butterfly wings



The flow required to prevent diffusion

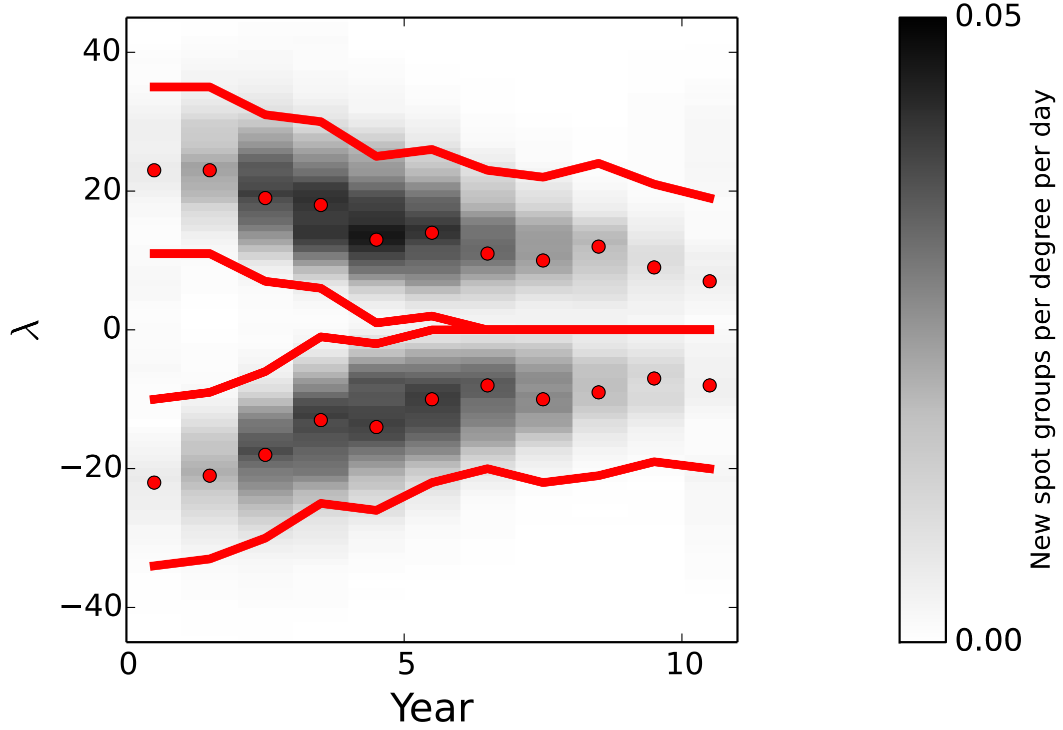


$$\nabla \times (\mathbf{U} \times \mathbf{B}) = \nabla \times \eta_{\mathrm{turb}} \nabla \times \mathbf{B}.$$

Terms relevant for latitudinal expansion: $\underbrace{U_\theta B_\phi}_{\text{Advective}}$, $\underbrace{U_\phi B_\theta}_{\text{Source}}$, $\nabla \times \underbrace{\eta_{\mathrm{turb}} \nabla}_{\text{Diffusive}} \times \mathbf{B}.$

Source is distributed, and is locally substantially smaller than the other two terms (in the Sun).

The flow required to prevent diffusion



$$-\frac{1}{r}\frac{\partial U_\theta B_\phi}{\partial \theta} = \frac{\eta}{r^2 \sin(\theta)}\frac{\partial}{\partial \theta}\left(\sin(\theta)\frac{\partial B_\phi}{\partial \theta}\right) - \frac{\eta B_\phi}{r^2 \sin^2(\theta)}$$

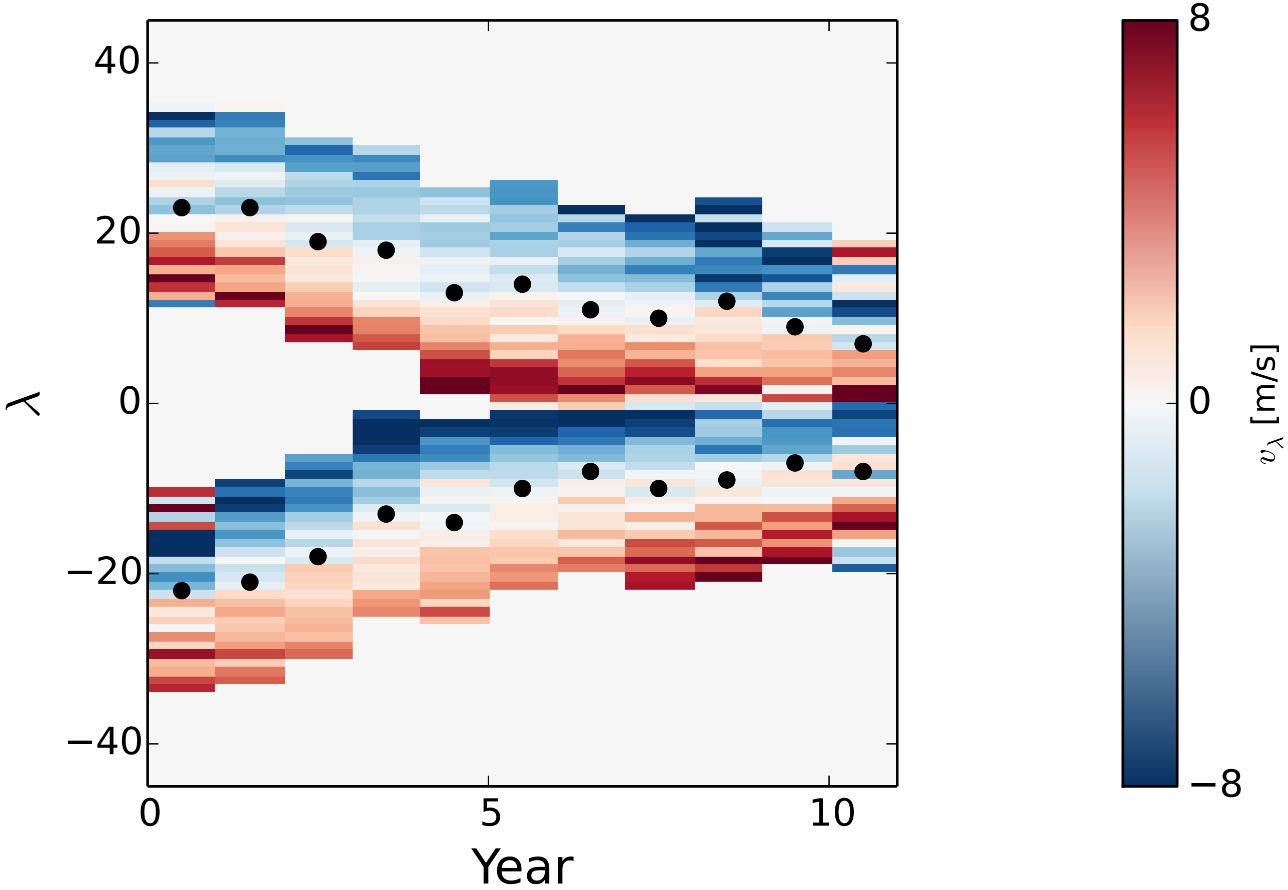
$$-\frac{1}{r}\frac{\partial U_\theta B_\phi}{\partial \theta} = \frac{1}{r}\frac{\partial}{\partial \theta}\left(\frac{\eta}{r \sin(\theta)}\frac{\partial \sin(\theta) B_\phi}{\partial \theta}\right)$$

$$U_\theta B_\phi = \frac{\eta_{\mathrm{turb}}}{r \sin(\theta)}\frac{\partial \sin(\theta) B_\phi}{\partial \theta}.$$

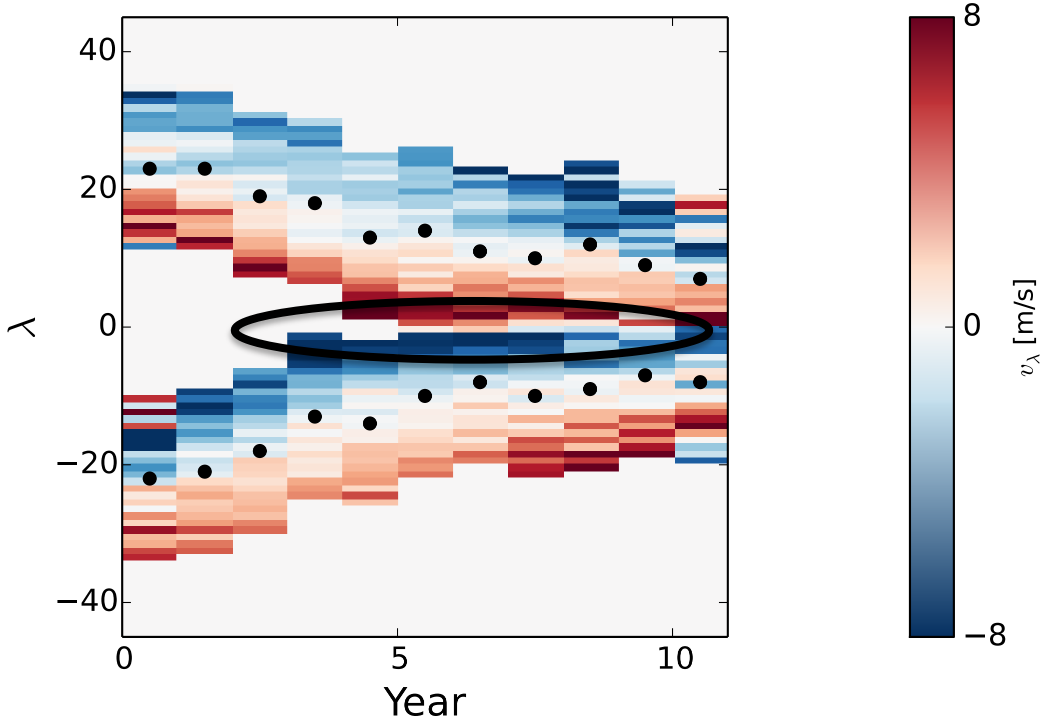
$$U_\theta = \frac{\eta_{\mathrm{turb}}}{r \sin(\theta) B_\phi}\frac{\partial \sin(\theta) B_\phi}{\partial \theta}.$$

The flow required to counter diffusive expansion

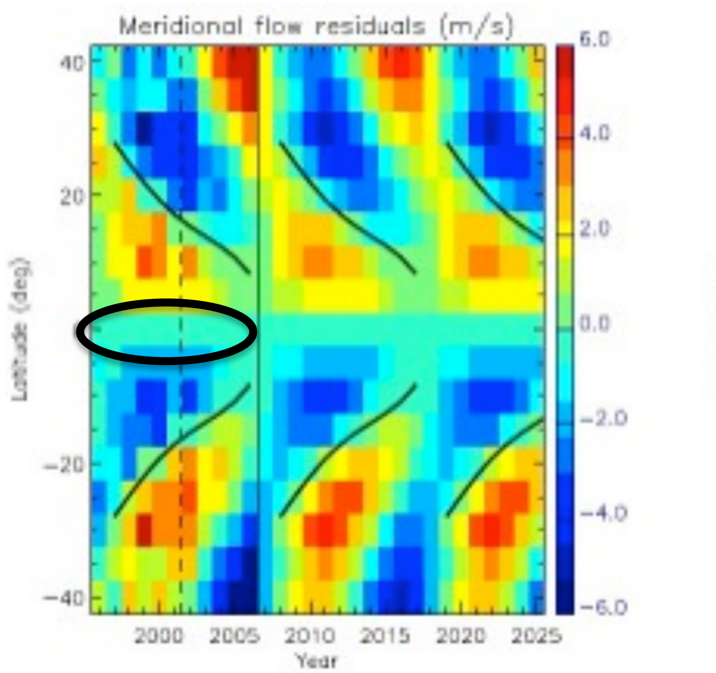
$$U_\theta = \frac{\eta_{\rm turb}}{r\sin(\theta)B_\phi}\frac{\partial \sin(\theta)B_\phi}{\partial\theta}.$$



Flow required to counter diffusive expansion



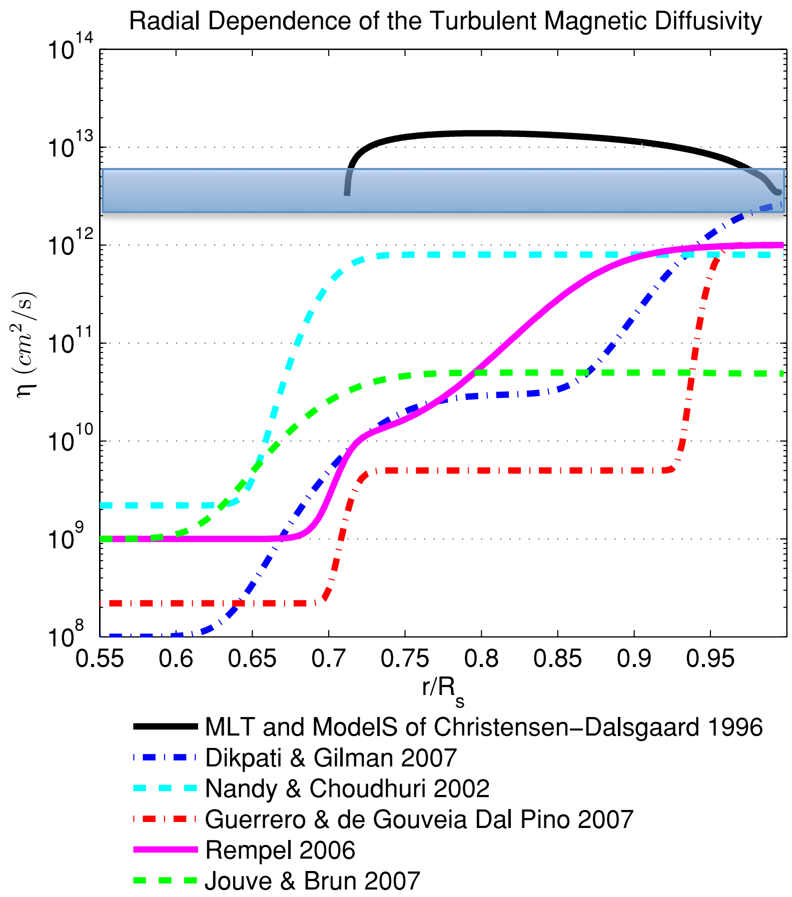
Observed inflows at the surface,
return flow at 50Mm(?)



Strong flows near equator to counter diffusion are not present in the observations – this is why we have strong cross-equator diffusion.

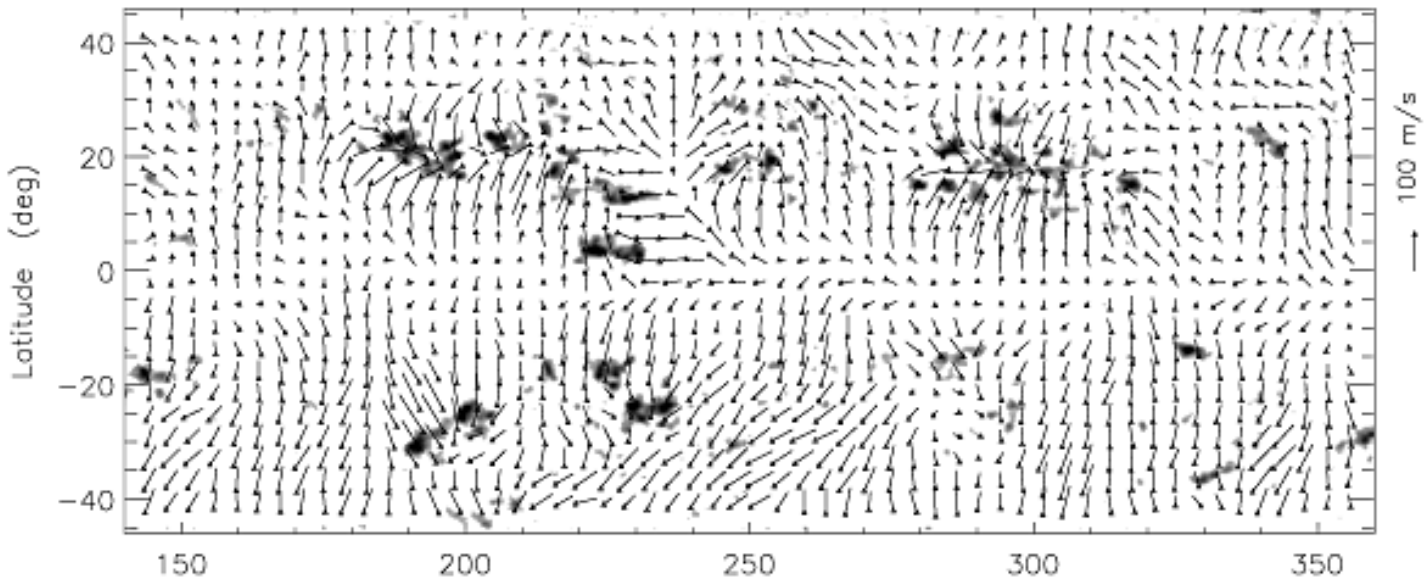
Conclusions: III

- Inflows into activity belt necessary to maintain butterfly wings.
- Butterfly diagram is essentially nonlinear.



- Toroidal field is located close to the surface

The inflows are not axisymmetric



Gizon et al 2001

Questions.